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Developing a self-optimizing forming system

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Abstract

The forming process is nonlinear, and it is difficult to clearly understand forming mechanism and deformation law of workpiece during forming process. In addition, the disturbances such as inhomogeneous material of workpiece, high temperature, roller wear, etc., often occur during forming. These disturbances cause the inaccuracy of the pulley geometric shape and reduction of the product quality. To handle this challenge, first a 3D-FE simulation was executed to investigate the deformation behavior of workpiece and to find the forming parameters. In the next step, a self-optimizing strategy was developed as a control system to improve the product quality. This self-optimizing approach is being practiced in the real forming machine system for validating the efficiency of the proposed strategy.

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Keywords: Spin forming process; self-optimizing system; modeling and controlling; FE numerical simulation; artificial neural network.

1. Introduction

Nowadays, pulley manufacturing systems for the automotive industry become more and more competitive due to the increment of the customer demands such as the high product quality, low price, and shorten delivery. In order to produce a pulley, the splitting spinning technology was applied. This technology is known as one of the new rising, green flexible forming technologies [1]. It is designed to split a rotational workpiece from outer edge into two flanges using a splitting roller with shape according to design, and then the complete product is made by the other steps (rolling, turning). This technology is widely applied to manufacture the pulley types in fields of automobile,

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train, and aerospace. Figure 1 shows some pulley productions in automobile industry which produced by splitting spinning technology.

Fig. 1. Pulley products produced by forming technology.

Until now, three methods for studying the splitting spinning process consist of theoretical analysis [1, 2], experiment [3], and FE numerical simulation [4], [5], [6]. First two methods have used to solve the simple problems, while the plastic deformation has complicated behaviour. FE numerical simulation method helps to clearly understand a fundamental forming mechanism, the influences of forming conditions (vibration, temperature, distortion, tool wear, etc.) to the forming quality, and defects of products during forming. In addition, this technology also gives an efficient method for identifying and optimizing important parameters without the need of expensive experience [4]. In order to understand the forming mechanism and to find the forming parameters, a reasonable 3D-FE model of forming process was first developed in accordance with real working condition. After that the simulation was executed in established model. Based on the simulation results, a self-optimizing forming system was established as a control system for resolving the mentioned troubles. This paper is organized as follows: analysis of the principle and modelling of the pulley forming process are described in Section 2. A self-optimizing forming system is presented in Section 3. Finally the evaluation method and conclusion are discussed.

2. Analysis of operation principle and modeling the pulley forming process

2.1. Pulley forming principle

Figure 2 presents the principle of forming process.

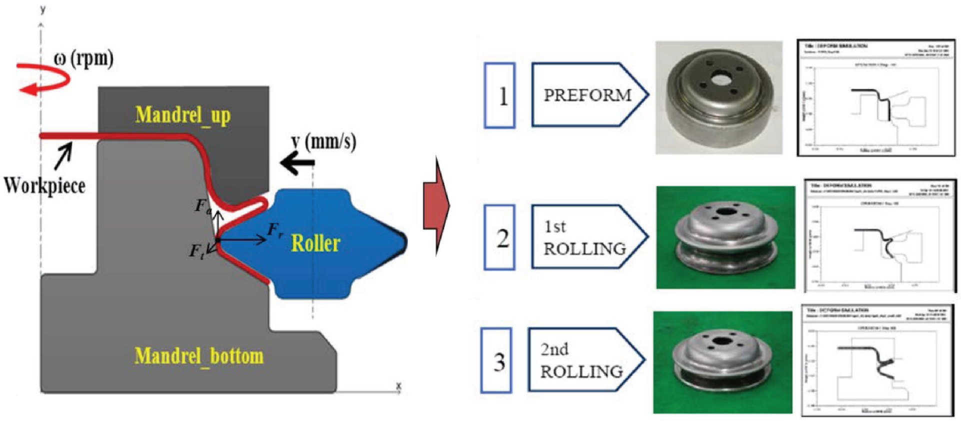


Fig. 2. Principle of the pulley forming process.

There are three main steps for simulating the forming process including the preform step, the 1st rolling step, and the 2nd rolling step. In this study, the 2nd rolling step called Splitting-process is considered as a main step which decides the pulley product quality. The operation principle of splitting spinning forming process is described as follows: the workpiece is first clamped on two mandrels and rotated with a rotational speed (ω) of the mandrels, and then a roller is controlled to move horizontal direction with speed (v) against the material at the outer side of workpiece as splitting forming. The material is variously deformed into two flanges begin from outer edge of workpiece to the goal point. After the forming is finished, the outer diameter of the workpiece reduces, and pulley is produced, as shown in Figure 2.

Actually, the pulley forming is nonlinear process which involves the disturbances of forming condition such as vibration, high temperature, low pressure, roller wear, and deformation phenomena of material such as flow, distortion, fracture. These phenomena are related with the material properties such as yield stress (σ_s), hardening exponent (n), and elastic modulus (E). Therefore, it is very difficult to understand purely by analytical and experimental methods. In order to clearly understand the forming parameters which main influence to pulley quality, several studies have been addressed to develop a 3D-FE simulation model [4], [5], [6]. These research results proved the FE numerical simulation results are in good agreement with the experimental results. In our study, FE numerical simulation technology first was used to investigate the workpiece deformation and then find the forming parameters which are necessary for developing a self-optimizing forming control system. A proposed 3D-FE model presents in the detail in next section.

2.2. Developing a 3D-FE model of pulley forming process

Based on analyzed forming principle above, a 3D-FE model of forming process is established in ABAQUS/Explicit environment. This model includes two mandrels, workpiece, and splitting roller. Two mandrels and roller are defined as the analytical rigid bodies and workpiece is defined as a 3D deformable solid body. The splitting roller and mandrel up are assigned with a reference point (RP). These reference points represented their rigid motion in all degrees of freedom. The 3D-FE model of forming process is shown in Figure 3. The parameters values of 3D-FE model are given in Table 1. The setting values for simulation are shown in Table 2.

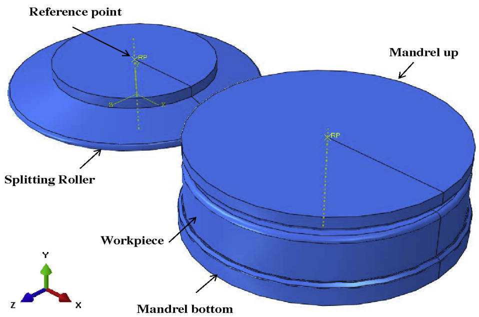


Fig. 3. A 3D-FE model of pulley forming process developed in ABAQUS/Explicit.

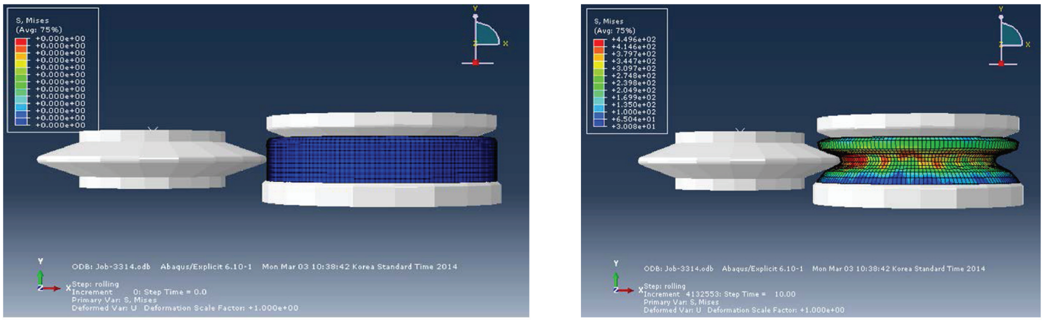
Table 1. Parameters values of 3D-FE pulley forming model.

Parts	Dimensions	Material
Workpiece	- Initial diameter (D_w): 100 *mm* - Initial height (H_w): 20 *mm* - Initial thickness (t_o): 3 *mm*.	Steel (Deformable body)
Roller	- Diameter (D_r): 100 *mm* - Splitting angle (2α): 48^0 - Roller nose radius (ρ_r): 2 *mm*.	Steel (rigid body)
Mandrels	- Diameter of Mandrel up (D_{mu}): 100 *mm* - Diameter of Mandrel bottom (D_{mb}): 100 *mm*.	Steel (rigid body)

Table 2. Values of the simulation parameters.

Parameters	Simulation condition
Workpiece material properties	E = 150 *GPa* ν = 0.3 ρ = 7850 *kg/m*^{3}
Mandrel speed	ω = 150 *rpm*
Roller velocity	v = 0.8; 1.0; 1.15; 1.25; 1.35; 1.5 *mm/s*
Friction coefficients	μ_{w-r} (workpiece-roller) = 0.05 μ_{m-w} (mandrel-workpiece) = 0.01

The FE simulation of forming process is executed on 3D-FE model under the given parameters in Table 2. During simulation, two mandrels rotate at constant rotation speed (ω), and roller moves to workpiece in radial direction at linear speed (v). Under the effects of the friction between the roller and workpiece and the extrusions of two mandrels, the pulley is produced as shown in Fig. 4b. The simulation results of forming forces are shown in Fig. 5.



(a) (b)

Fig. 4. FE simulation of forming process in ABAQUS/Dyanmic explicit: (a) Beginning of FE simulation; (b) finished simulation.

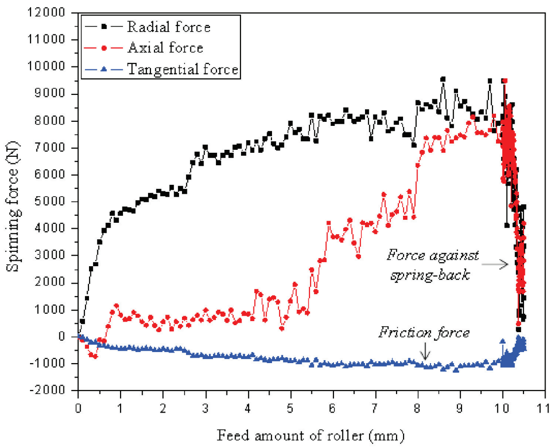


Fig. 5. Variations of forces corresponding to roller displacement.

The evaluation of simulation results on Fig. 4b: As the forming continues, stress zone of workpiece is similar a belt which its width gradually expands along with time. When roller feed amount increases deformation of workpiece increases, and stress concentration occurs in contact zone between roller and workpiece more and more. The distribution of equivalent stress is not-uniform and there are some stress concentrations in concaves. The stress disappear when the forming process end. Consequently, based on the forming results of obtained deformation and equivalent stress, the forming process parameters can be determined and optimized with help of the established 3D-FE model.

The evaluation of simulation results on Fig. 5: The obtained forming forces can be categorized into three components such as radial force, axial force and tangential force. The radial force is a main force for driving. Hence, it is the most valuable in three spinning forces. The radial force increases with the increase of roller feed amount. The axial force occurs at the time of the appearance of two flanges, which is symmetrical fluctuating distribution. Meanwhile, the tangential force appears owing to circumferential friction. Due to a small value of friction coefficient is used in this study. Hence, the tangential force almost keeps invariable till the forming process end. In this study, the radial force is considered as main force component for optimizing forming process.

3. Developing a self-optimizing forming system

According to authors [7], a self-optimizing system is able to optimize its behavior by adapting the structure of utilized mechanical components when the system is facing disturbances by the environment. Optimization is a usual step of control design. To do this, design goals have to be clearly defined and system information must be sufficient supplied. However, in forming process, due to the complexity of deformation behavior and unknown disturbances, design goals may change during operation. Hence, it is difficult to control the roller for ensuring the product quality based on the conventional control system.

In order to optimize the forming process, design goals of forming control system must be defined. There are two goals of the forming control system including the roller displacement and the forming force. To develop a self-optimizing control system for forming process, two objective functions of the roller displacement and the forming force firstly must be established.

The objective function of roller displacement is determined based on the deviation between the measured displacement and ideal displacement of roller. Meantime, the force objective function is determined based on the ideal force performance. A systematic procedure for developing a self-optimizing forming system is shown in Fig.6.

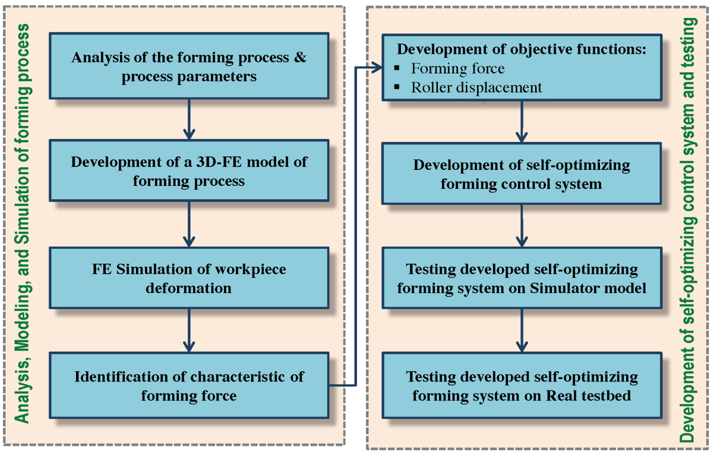


Fig. 6. Systematic procedure for developing a self-optimizing forming system.

Based on the FE simulation results of forming process under ideal working condition, the force standard characteristic corresponding to workpiece material is identified. The identified force curve is considered as force objective function which is necessary for developing a self-optimizing forming control system. To identify the forming force curve, a neural network algorithm is used. Neural network has been applied very popularly and successfully in the identification and control of the nonlinear system. Whereas, the multilayer perception has known as best select to identify the nonlinear system and design the nonlinear controller. There are two steps to make a neural network controller, includes the system identification and the control design.

3.1. Identification of pulley forming process

In system identification stage, a neural network algorithm is used to identify the state of forming process and estimates the control parameters. The relationship between disturbances and forming behavior can be learned by neural network. The training process is a representative model of the forward dynamic of the forming process. After training, this network can be used to design the controller for the forming process. In this stage, the ideal workpiece deformation data which obtained from FE numerical simulation is used to train the neural network. The inputs variables of neural network are the roller velocity and forming force. Meanwhile, the output variable is the approximately deformation. The prediction error between the forming process output and the neural network output are used as the neural network training signals. The training diagram for forming process is presented in Fig. 7. Identified forming process model can be used to establish a forming simulator model for testing the proposed self-optimizing strategy.

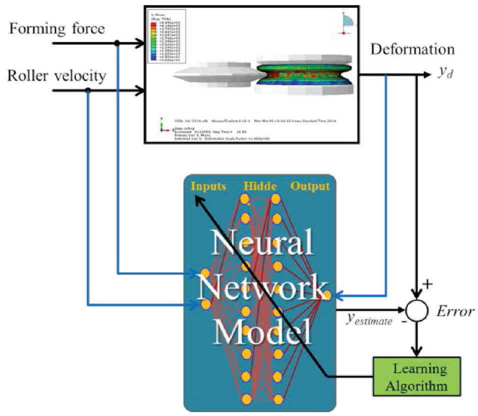


Fig. 7. Forming process identification model.

3.2. Design of self-optimizing control system

A proposed self-optimizing control system allows compensating for nonlinear system in disturbance cases. Diagram of proposed self-optimizing control system for forming process is shown in Fig. 8. An inverse-dynamic model of forming system is used to generate the estimated force values based on knowledge of system dynamics. The deviation between measured force and estimated force should be minimized during forming process.

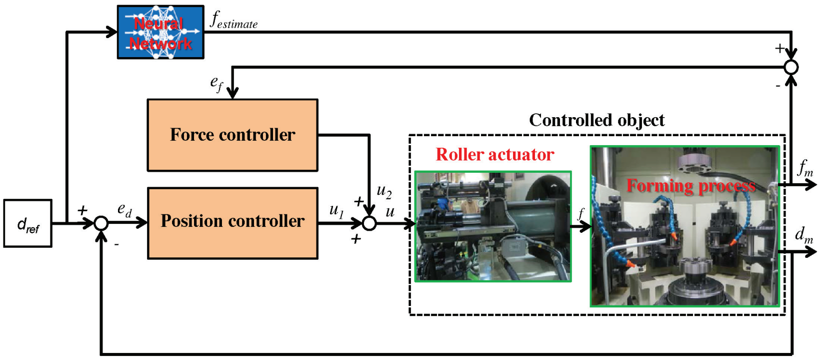


Fig. 8. Diagram of proposed self-optimizing forming control system.

The control system of forming process involves two controllers, a position controller and a force controller. The position controller has responsibility for controlling the roller tracks the reference displacement. It minimizes displacement errors (e_d) during forming in disturbance cases. Meanwhile, the force controller is to keep forming force in limited range based on the force objective function.

4. Evaluation and conclusion

In order to evaluate the efficiency of the proposed self-optimizing forming system, we make a survey on the conventional pulley forming systems of KAPEC Company. The collected production data of the conventional pulley forming system are given in Table 3. Every 2 operation hours the forming system should be stopped for the product inspection (10 *mins*). And after 14 operation hours the system must be stopped for change tool (20 *mins*). Therefore, the production efficiency of the pulley forming system in one week can be calculated as follows:

$$\eta_{cfs} = \frac{14hrs \times 60\,pc\,/\,hr \times (40 - 3.667)}{25hr \times 60\,pc\,/\,hr \times 40} \approx 51\% \tag{1}$$

By applying the self-optimizing forming system, the control system can automatically adjust the roller velocity according to the predicted spinning forces. Therefore, the roller life extends and the disturbances can be eliminated. The simulation results on the forming simulator shows that the product quality guarantee and the production efficiency increases more *30%* compared to the conventional system.

Table 3. The collected production data of the pulley forming system in KAPEC Company

Production data in KAPEC	Values
Product Rate	60pc/h
Tool change time	20min
The given tool life	25hr
Average life of the used tool	14hr
Inspection period	Every 2hrs
Inspection time	10min

In this paper, the self-optimizing forming system was presented. The FE numerical simulation technology combine with the artificial intelligent algorithm were applied in the pulley forming system. In this approach, the workpiece deformation was investigated and the forming parameters are identified. Based on the identified system, the self-optimizing control system was designed and tested on the forming simulator. This proposed strategy will be verified on the pulley forming system in KAPEC Company.

Fig. 9. The pulley forming system testbed in KAPEC Company.

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